

# How Accurate is a Radio Controlled Clock?

Michael A. Lombardi

The advertisements for radio controlled clocks and wristwatches often make sensational claims about the accuracy of their products. One overly enthusiastic writer penned this memorable bit of ad copy:

*“We’re still perfecting Einstein’s theory. We must apologize that our Atomic Watch loses 1 second every 20,000,000 years. Our scientists are working diligently to correct this problem ....”*

While this particular advertisement contained more hyperbole than most, it was not alone in referring to a radio controlled clock (RCC) as an atomic clock, a claim made in nearly all sales pitches and product literature. The claim is, of course, false. The oscillator found inside an RCC is similar to those found in all quartz clocks. It oscillates based on the mechanical vibrations of a quartz crystal, typically counting 32,768 vibrations of the crystal to mark one second. A true atomic clock oscillates based on the energy transitions of an atom and “ticks” much faster. For example, the second is defined internationally as the duration of 9,192,631,770 energy transitions of a cesium atom.

Although advertisers are wrong when they call an RCC an atomic clock, they are correct in asserting that an RCC benefits from atomic timekeeping. An RCC periodically synchronizes its quartz oscillator to a real atomic clock by receiving a time signal from one of the radio stations listed in Table 1. Some RCCs are capable of receiving just one station, and must be within the coverage area of that station in order to work. Others, including many wristwatches, are now capable of receiving all of the stations in Table 1 and will synchronize to the signal from the nearest station, **1**.

*Table 1. Time Signal Stations used by RCWs*

Station Call Sign	Frequency (kHz)	Country	Controlling Organization
BPC	68.5	China	National Time Service Center (NTSC)
DCF77	77.5	Germany	Physikalisch-Technische Bundesanstalt (PTB)
JJY	40, 60	Japan	National Institute of Information and Communications Technology (NICT)
MSF	60	United Kingdom	National Physical Laboratory (NPL)
WWVB	60	United States	National Institute of Standards and Technology (NIST)

Now that we’ve established that a RCC is not a real atomic clock, but simply a quartz clock periodically adjusted by radio, can we determine its true accuracy? The answer is yes, but at least four questions first need to be answered:

- How accurate is the time kept at the radio station?
- How long does it take for the radio signal to travel from the station to the RCC?

- When the signal arrives, how accurately is the RCC's display synchronized?
- How accurate is the RCC's quartz crystal oscillator in between synchronizations?

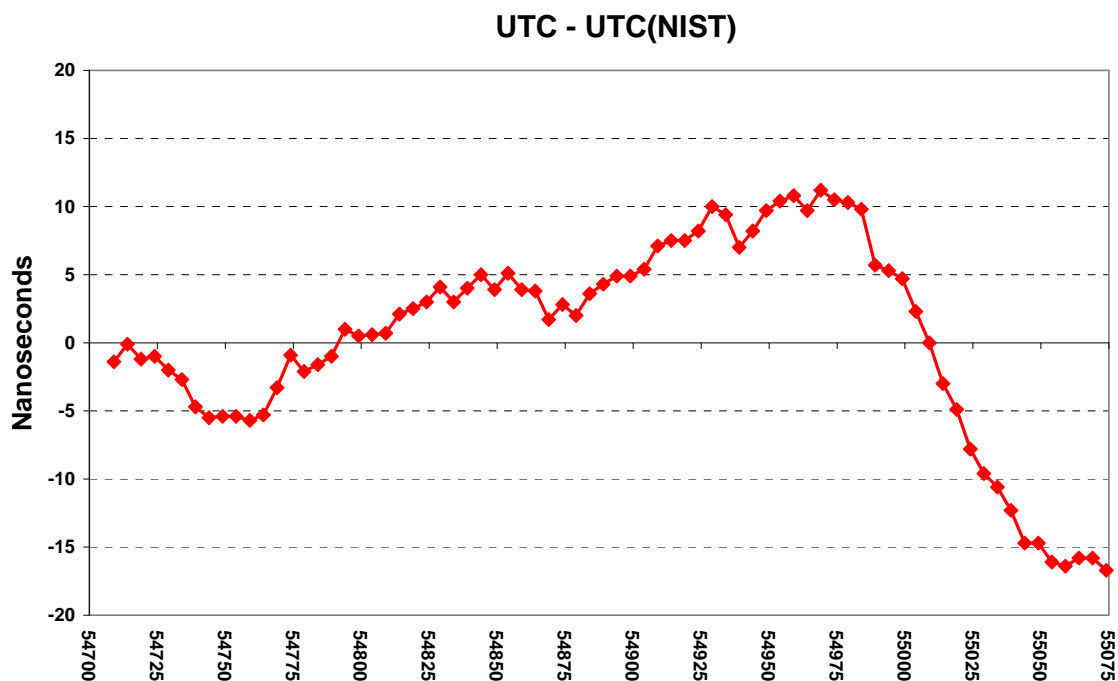
We'll look at each of these questions in turn, using the U. S. radio station WWVB (Figure 1) as an example.



*1. Aerial view of NIST time signal station WWVB.*

### **Q1. How accurate is the time kept at the radio station?**

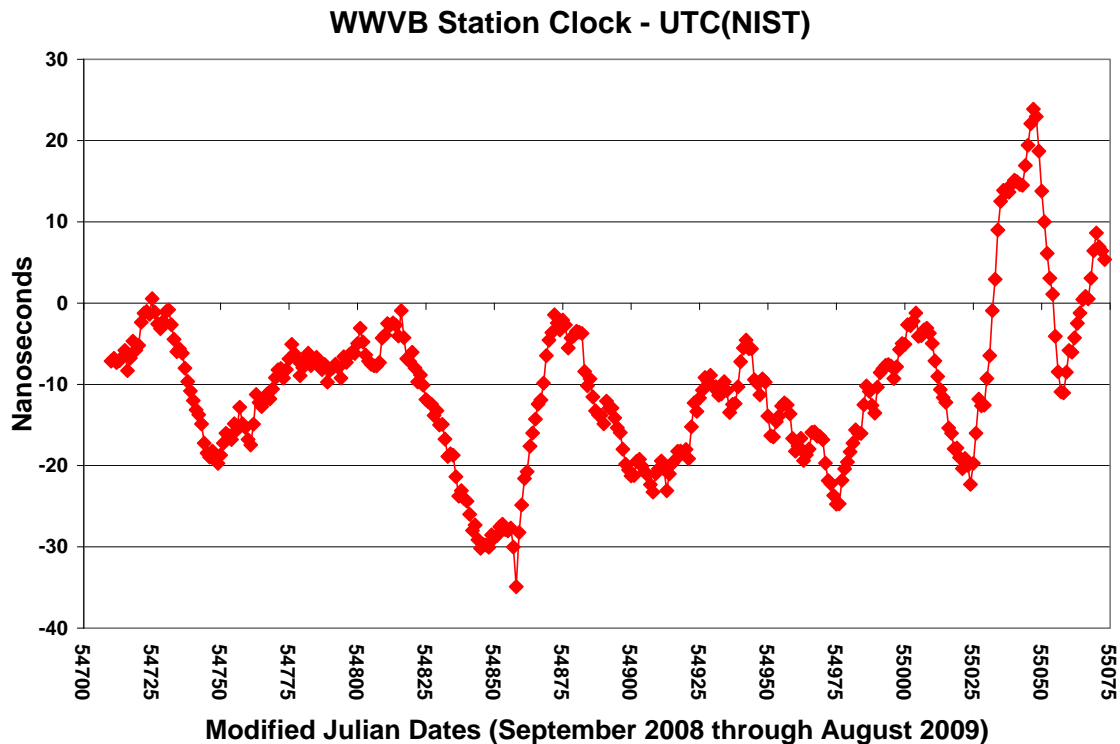
Time signal stations synchronize their clocks to Coordinated Universal Time (UTC), the international standard for timekeeping. No clock can keep UTC exactly, because UTC is an average time, calculated with data collected from hundreds of atomic clocks located around the world. The calculations are performed by the *Bureau International des Poids et Mesures* (BIPM) in France. Laboratories such as the National Institute of Standards and Technology (NIST) keep local versions of UTC that closely agree with the BIPM's calculations. Figure 2 shows the time difference between UTC(NIST) and UTC over a one-year period with the data points taken at five-day intervals, 2. Note that UTC(NIST) never varied from UTC by more than 20 nanoseconds during the year. A nanosecond is  $1 \times 10^{-9}$  seconds, or 0.000 000 001 s. Thus, while there is technically a difference between UTC(NIST) and UTC, the difference is miniscule and for all practical purposes can be ignored.



2. UTC(NIST) Time Scale compared to Coordinated Universal Time

The time signal stations listed in Table 1 are located some distance away from the timing laboratories that control them, typically in a rural area where there is enough space for their antennas. For example, the NIST timing laboratories are in the city of Boulder, Colorado, and WWVB is located in a rural area about 78 km away. Therefore, UTC(NIST) in Boulder is not directly connected to WWVB. Instead, WWVB has its own clock, actually a group of cesium clocks, that are steered to agree with UTC(NIST) in Boulder by making time comparisons using satellites, 3.

Figure 3 shows the difference between UTC(NIST) and WWVB station time over the same one year interval shown in Figure 1 (here the data points are at 1-day intervals). Note that the station clock never varied from UTC(NIST) by more than 35 nanoseconds. Again, for all practical purposes, the differences are so tiny they can be ignored. In fact, the frequency offset of the station clock is less than  $1 \times 10^{-15}$ . If this frequency offset were held constant, it would take more than 30 million years before the accumulated time error reached one second. If the advertising writers were referring to the station clock, and not the RCC, you could actually argue that they were being conservative.



### 3. *WWVB Station Clock compared to UTC(NIST) Time Scale*

## **Q2. How long does it take for the radio signal to travel from the station to the RCW?**

The exceptional accuracy of the station clock becomes a moot point once you start to consider the problem of path delay. There is some path delay before the signal even leaves the radio station. Once the time signal is generated from the station clock, it passes through a transmission system that includes the radio transmitters; the antenna feed lines, and the antennas themselves. At WWVB this delay is about 0.000 017 s, **4**, or about one thousand ( $10^3$ ) times larger than the time difference between the station clock and UTC. Even so, it is still too tiny to matter to RCC users, so the station does not advance its signal to compensate for the transmission delay.

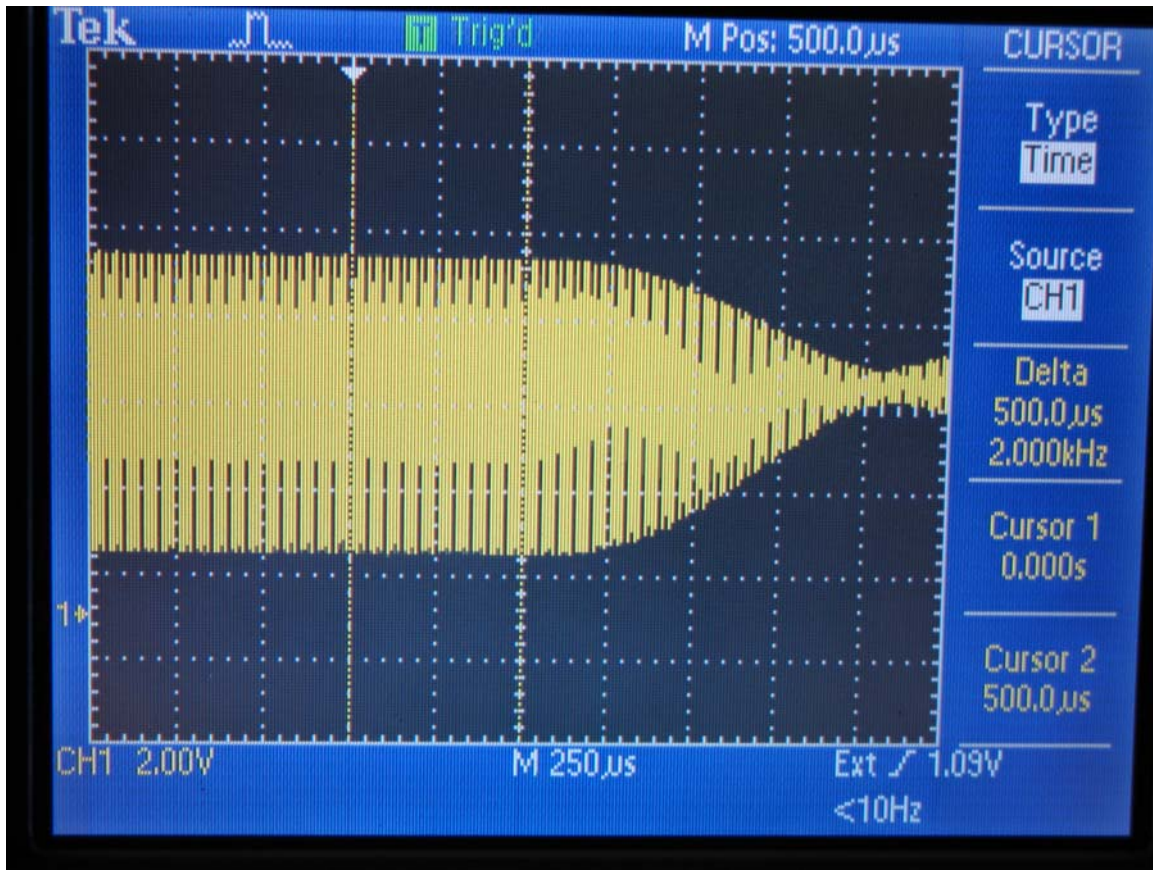
Once the signal leaves the transmitter and enters free space, it travels at the speed of light to the RCC, approximately 0.000 003 336 seconds per kilometer. If you know the location of your RCC and the location of the time signal station, you can calculate the distance between the transmitter and the receiver, and estimate the amount of this delay. For example, a 3000 kilometer path would delay the time signal by about 10 milliseconds (0.01 s). This assumes, of course, that the signal travels along the ground and covers the shortest possible distance between the station and the RCC. For the low frequencies used by the time signal stations in Table 1, a “groundwave” path can be assumed for short distances, perhaps up to 1500 km, but at longer distances the signal might bounce off the ionosphere and have a path delay slightly larger than the calculation. Even so, the path delay will probably always be less than 20 milliseconds (0.02 s) because the signal will seldom be usable at distances of more than 5000 km and any additional delays introduced by skywave will seldom exceed 1 millisecond. However, note that for RCCs

located on the east and west coasts of the United States, the path delay is about one million times ( $10^6$ ) larger than the time difference between the station clock and UTC.

### **Q3. When the signal arrives, how accurately is the RCW's display synchronized?**

The modulation used by the time signal stations in Table 1 is very simple. For example, WWVB broadcasts a continuous 60 kHz signal, but drops the carrier power by about 98 % (17 dB) every second, restoring it to full power a fraction of a second later. This power drop serves two purposes. Its first purpose is to send bits of the time code, as the amount of time that the power is held low determines whether a bit is a 0, a 1, or a frame marker. A complete time code is 60 bits long and thus requires 60 s to transmit. The second purpose of the power drop is to send an on-time marker (OTM) that is synchronized with UTC(NIST). The OTM is the first 60 kHz cycle that is sent at reduced power. For example, when the power is held low for 0.2 seconds to signal a 0 bit, 12,000 cycles are transmitted at low power, but only the first of these reduced power cycles is the OTM. In theory, an RCC should be able to synchronize to within one half of the period of 60 kHz, or to within  $\pm 0.000\ 008$  s of the OTM.

In practice, there are other problems. One is the quartz crystal oscillator inside an RCC runs at a frequency of about half of the incoming radio signal (32.768 kHz), and thus even if the correct OTM were found, the quartz crystal could still only be synchronized to within half the period of its own cycle, or to within about  $\pm 0.000\ 015$  s. As it turns out, that doesn't matter because it is very difficult for the RCC to find the correct OTM. The WWVB waveform (Figure 4) has a long exponential decay that is related to the period of the antenna bandwidth making it very difficult to determine exactly where the carrier power drop began. The actual OTM is located in the flat part of the waveform, before a noticeable drop in amplitude can be seen on an oscilloscope. Practically speaking, the OTM synchronization accuracy is probably limited to half the period of about 30 cycles, or  $\pm 0.000\ 250$  s, **4**, although the actual accuracy will depend upon the quality of both the received signal and the RCC's digital signal processing (DSP) firmware.



4. WWVB OTM as seen on an oscilloscope.

Larger delays occur after the before the display and/or the watch hands can be synchronized to the right time. These processing delays include DSP software delays, the time required to retrieve the data from the microprocessor unit and to process and output the data, and the response time of the stepping motor used by analog clocks or the LCD display used by digital clocks. The processing delays can sometimes exceed 100 milliseconds (0.1 s), but the RCC manufacturer normally takes them into account, and advances the hands or display to compensate. Even so, the amount of delay that needs to be compensated for is not going to be perfectly estimated, and a synchronization error of 10 milliseconds (0.01 s) is probably not uncommon.

Table 2 summarizes the accuracies discussed in the answers to first three questions. Based on this analysis, it seems reasonable to expect that an RCC will be accurate to within 30 milliseconds (0.03 s) at the time of synchronization, with the path delay and synchronization errors the only two factors that really matter. However, a much larger time error is likely to accumulate during the interval between synchronizations, as will be seen in the answer to question 4.



*Table 2. Sources of RCC synchronization inaccuracy*

Source of inaccuracy	Seconds
Radio station clock	0.000 000 010
Transmission system delay	0.000 017
Path delay (worst case)	0.020
OTM selection	0.000 250
Synchronization errors	0.010
RCC inaccuracy at time of synchronization	~0.03

#### **Q4. How accurate is the RCC's quartz crystal oscillator in between synchronizations?**

Some RCCs only schedule one synchronization attempt per day, at 2 a.m., for example. If the synchronization attempt fails, they will wait 24 hours before trying again. Others are designed to schedule multiple attempts (at 2, 3, 4, and 5 a.m., for example). In some cases, they will attempt synchronization during each of their scheduled times, synchronizing again at 3 a.m. even if the 2 a.m. attempt was successful. In other cases, they will skip the remaining attempts on the schedule after synchronization is achieved and wait until the next day to try again. For these reasons, the interval between synchronizations is either 24 hours, or just a few hours less.

It might seem reasonable to make more synchronization attempts because time signal stations broadcast 24 hours per day. However, the number of synchronization attempts is limited for several reasons. One reason is that the signal is much stronger at night and synchronization attempts during the daytime hours are far more likely to fail. A second reason is that many RCCs are battery powered, and fewer synchronization attempts means longer battery life. The most important reason is that one successful synchronization attempt per day is all that is needed to always keep an RCC accurate to within a fraction of a second of UTC.

The National Institute of Standards and Technology (NIST) has published guidelines recommending that RCCs keep time between synchronizations to within  $\pm 0.5$  s of UTC(NIST). If this requirement is met, the time displayed on an RCC will always be correct when rounded to the nearest second, **5**. At least one manufacturer of RCCs specifies the accuracy of their quartz crystals as  $\pm 15$  s per month, which is essentially the same thing as  $\pm 0.5$  s per day. This type of accuracy is now commonplace, **6**, and translates to a frequency offset of about  $6 \times 10^{-6}$ , more than one billion ( $10^9$ ) times less accurate than the station clock!

While  $\pm 0.5$  s per day is a reasonable benchmark, synchronization to within  $\pm 0.2$  s is desirable and achieved by many RCCs. An 0.2 s error is unlikely to be noticed by the human eye if an RCC is checked against an independent time reference, whereas a 0.5 s error might be. Even if an RCC can keep time to within 0.2 s between synchronizations, the accumulated time error between synchronizations will be much larger than the other factors listed in Table 2. This means that an RCC will be most accurate immediately after a successful synchronization and will become less accurate from that point forward until the next synchronization.

To demonstrate this, a measurement was made of the accumulated time error of an analog wristwatch in between synchronizations. A sensor was used (Figure 5) that could record the beat rate of the watch's stepping motor pulses. At the time of synchronization, it is assumed that the time error was 0, although in reality the synchronization accuracy is limited by the factors shown in Table 2. The assumption had to be made because the second hand stops during synchronization, which in turns stops the sensor from collecting data. However, since the watch was operating near WWVB (the path delay was about 0.000 26 s), it was probably accurate to within 0.01 s of UTC(NIST) at the time of each synchronization.

Figure 5 goes here

The measurement results are shown in Figure 6. The watch synchronizes five times daily, at midnight, 1, 2, 3, and 4 a.m. The midnight synchronization occurs after the quartz crystal has free run for about 20 hours, and the amount of the correction is about 0.45 s. The other four synchronizations occur after the quartz crystal has free run for about one hour, and the correction is slightly larger than 0.02 s. This particular watch meets the requirement of always remaining within half a second of UTC(NIST), but not by a comfortable amount. If it synchronized only once every 24 hours, it would narrowly miss the requirement. Its performance can be considered typical of many RCC products.

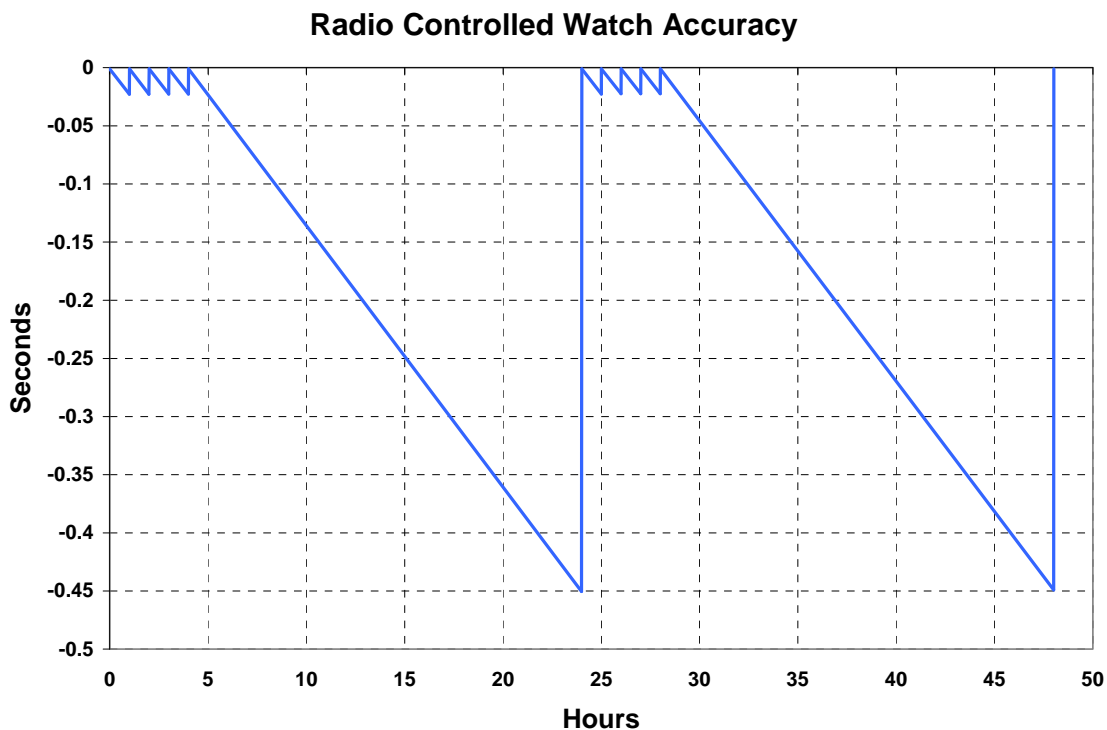


Figure 6 – Graph showing corrected phase

To return to our original question: How accurate is a radio controlled clock? The short answer is they should always be accurate to within one second of UTC, assuming that they synchronize at least every other day and that their quartz oscillator is of reasonable quality. The key, of course, is successful synchronization to a time signal station, because without that advantage an RCC is



just a run of the mill quartz clock. Instead of the “20,000,000 years” mentioned by the ad writer, the watch measured in Figure 6 would lose a second in about 2 days if it was unable to synchronize. On the other hand, if a RCC could miraculously be made to run for “20,000,000 years” and was somehow able to synchronize once every 24 hours, it would lose less than 1 second. Such are the benefits of atomic timekeeping.

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- 1 M. A. Lombardi, *Radio Controlled Wristwatches*, HJ, 148(5), May 2006, pp. 187-190.
- 2 *BIPM Circular T* (numbers 249 through 260), available at: [www.bipm.org](http://www.bipm.org)
- 3 J. Levine, *Realizing UTC(NIST) at a Remote Location*, Metrologia, 45, pp. S23-S33, December 2008.
- 4 G. K. Nelson, M. A. Lombardi, and D. T. Okayama, *NIST Time and Frequency Radio Stations: WWV, WWVH, and WWVB*, NIST Special Publication 250-67, 161 pages, January 2005.
- 5 *WWVB Radio Controlled Clocks: Recommended Practices for Manufacturers and Consumers*, NIST Special Publication 960-14, 68 pages, August 2009.
- 6 M. A. Lombardi, *The Accuracy and Stability of Quartz Watches*, HJ, 150(2), February 2008, pp. 57-59.